Atmospheric Multiple Scattering Effects on GLAS Altimetry.
Part II: Cloud Climatology Analysis of Expected Seasonal and Interannual Surface Altitude Errors

revised version, submitted to IEEE Trans. in Geoscience and Remote Sensing
December 2000

Corresponding author address

Ashwin Mahesh
Mail Code 912
NASA Goddard Space Flight Center
Greenbelt MD 20771
Email: mahesh@agnes.gsfc.nasa.gov

ABSTRACT

The altimetry bias in GLAS (Geoscience Laser Altimeter System) resulting from atmospheric multiple scattering is studied in relationship to current knowledge of cloud climatology over the Antarctic Plateau., and estimates of seasonal and interannual changes in the bias are presented. The bias in altitude that is caused by multiple scattering in clouds can be several times the GLAS mission requirement of 1.5 cm. The selective use of thin clouds or cloud-free observations as well as improved analysis of the return pulse, such as the Gaussian method used here, are necessary to keep the altitude bias comparable to this value. The magnitude of the bias is affected by cloud height, cloud effective particle size and optical depth, and internannual variations in these quantities as well as in cloud cover could lead to significant year-to-year variations in the altitude bias. Cloud-free conditions too are not perfect for altimetry, since these may often include near-surface blowing snow with its own scattering-induced delay.

1. Introduction

With increasing concern over likely warming of the earth's surface, the need to develop and implement sound monitoring programs to detect potential large-scale changes at an early stage has also grown. The high-latitudes, and the marginal ice zones around the frozen ice shelves there, have been a particular focus, in the expectation that the first and largest signs of global change will be seen here, a view that has been bolstered by measurements of significant surface temperature changes in coastal Antarctic and Arctic regions in recent decades.

The Geoscience Laser Altimeter System (GLAS) is designed to measure and monitor a particular aspect of climate change in the high latitudes, namely changes in the mass balance of the Earth's large ice sheets, which are concentrated in the polar regions. It is believed that global climate warming could potentially alter the mass balance of these ice sheets, in turn leading to other climatic changes, notably a possible change in sea level. GLAS proposes to measure inter-annual changes in the thickness of polar ice sheets, and will provide the first estimates of continent-wide elevation changes in the Antarctic ice sheet.

The determination of ice-sheet mass balance is limited by typical methods, which rely on a comparison of two large numbers - total snow accumulation and total ice loss - that are each subject to large errors. Recently, more accurate methods to measure the ice-sheet mass balance have been developed using repeated altimetry measurements of the ice sheets by airborne lidar [1] and satellite radar [2]. These new methods each contain drawbacks; radar measurements are sensitive to surface slope errors and radar penetration into snow, and only a few lidar measurements over Greenland and Antarctica have ever been attempted. GLAS observations will mark an improvement on existing observations, and will measure temporal changes in the thickness of the Earth's polar ice sheets from space [3].

GLAS is scheduled to be launched in December 2001 as part of the Earth Observing System (EOS) mission. For the surface altimetry measurements, the mean elevation of the laser's surface spot will be estimated from the centroid of the return pulse. To permit the determination of mass balance changes, individual ice-sheet altitude measurements must be made with uncertainties smaller than 10 cm. A number of factors affect the accuracy of the altitude measurement, including surface slope, atmospheric propagation and signal noise. A cross-over technique that averages the elevation differences at selected points on the ice sheets is designed to reduce errors in order to measure mean ice elevation changes to an accuracy of 1.5 cm per year [4].

In Part I of this paper ([5] hereafter referred as DSE), the authors presented calculations of path delays by cloud and aerosol scattering from an analytic double-scattering model and Monte Carlo simulations of lidar surface returns. Both methods demonstrated that multiple scattering by thin polar clouds could seriously bias the altitude ranging of GLAS. If the surface height were measured from the centroid of the return pulse, a thin arctic stratus cloud with an optical depth of 0.5, a mean particle radius of 6 microns, and a thickness of 3 km would produce a to-and-fro path delay of 30 cm, corresponding to an altitude bias of 15 cm. Since the effect of multiple scattering is to always introduce a delay, the mean height change will be affected by the changes in cloud and aerosol overlaying the surface. Some clouds are sufficiently thick to block the laser signal from reaching the surface. Many polar clouds however are transmissive. The results of DSE will be discussed here in relationship to current knowledge of Antarctic cloud climatology, and potential impact of multiple scattering on GLAS altimetry measurements will be evaluated. The use of the atmospheric lidar signals of GLAS to eliminate such errors will also be discussed.

2. Variability of Cloud Properties on the Antarctic Plateau

Since the purpose of the altitude observations is to measure temporal changes in ice thickness, the ranging bias would not necessarily be a problem if polar cloud properties were fairly constant over time. Therefore, it is important to determine the seasonal and interannual variability of cloud properties. DSE found that several cloud parameters can affect the magnitude of multiple scattering-induced delays, including cloud optical depth, cloud particle size, and mean cloud height. The variability in each is now considered in turn.

a. Cloud Cover

Due to the harsh conditions in the Arctic and Antarctic, as well as their remoteness, observations of polar cloud properties have been far fewer than elsewhere. Even the most comprehensive cloud surveys such as Hahn et al. contain only sparse cloud data from the ice sheets over Greenland and Antarctica [6]. Despite this, some estimates of polar cloud characteristics can be made from current knowledge of polar cloudiness. The surveys of Hahn et al., for example, summarize surface observations of cloud cover across the globe. The observations indicate spatial variations in cloud cover over the poles. Figure 1 shows the mean annual total cloud cover in the Arctic from Hahn et al. [6]. Cloud cover is typically between 70 and 80 percent, with values over 80 percent in the area around Spitsbergen, and smaller amounts (between 55 and 70 percent) over western Greenland and northern Canada.

Most surface observations of cloud cover over Antarctica are from coastal stations which report values from 70 to 80 percent, while the few stations located in the interior of the continent report lower cloud amounts, typically varying between 40 and 60 percent. Observations of entirely clear skies are rare at the high latitudes; even stable surface temperature inversions under clear skies usually lead to the formation of near-surface ice crystals, known as diamond dust. The mean annual frequency of clear sky observations in the Arctic Ocean and the coastal stations of Antarctica is usually less than 10 percent [6].

Cloud cover also varies seasonally over the poles. Hahn et al. find that in winter, the cloud cover over most of the Arctic Ocean ranges from 50 to 70 percent. Arctic cloud cover is generally higher during the summer, when values range from 65 percent over western Greenland to over 80 percent over the Siberian Arctic. A similar seasonal cycle occurs over Antarctica, with higher values during the summer, and lower values during the winter. Mean wintertime cloud cover over the South Pole ranges from 30 to 40 percent, while in the summer, cloud cover varies from 45 to 70 percent at interior stations. Observations between 1971{1980 at the coastal Syowa Station (69 S, 39 E) show a more complicated seasonal variability incloud cover, with a maximum in the late summer of 79 percent and minima in the early summer (53%) and winter (60%) [7].

Hahn et al. also determined the interannual variation (IAV) in cloud cover over the poles [6]. IAV was defined as the standard deviation in seasonal cloud cover for the period from 1982-1991. The interannual variation in June-July-August (JJA) cloud cover for land stations in the Arctic was usually near 5 percent, and was near 10 percent for December-January-February (DJF) observations. Wintertime observations over the Arctic Ocean show IAV values from 20 percent north of Alaska to 2 percent over Spitsbergen. During the summertime the standard deviations ranged from 2 to 5 percent. The interannual variations at the Antarctic coastal stations and at the South Pole are generally near 5 percent.

The most recent year-long study of clouds over the Antarctic plateau is that of Mahesh et al (2000, in press). From ground based longwave spectral observations of clouds at South Pole station in 1992, the authors obtained an annual cycle of cloud base heights, particle effective radii and optical thicknesses. This study was not specifically designed to quantify fractional cloud cover throughout the year; Mahesh et al found clouds in approximately 43% of their spectral observations, roughly consistent with Hahn et al.'s multi-year average. Seasonal variation in cloudiness, by this measure, was found to be small.

b. Cloud particle size

The multiple-scattering induced path delays will also depend on the microphysical properties of the clouds. Curry et al. report that the most comprehensive measurements of wintertime ice crystal distributions show modal radii between 10 to 80 μm, and an average effective radius of 40 μm [8]. Summertime Arctic stratus, on the other hand, have much smaller mean radii, ranging from 2 to 7 microns.

In the Antarctic, Smiley et al. report that the most common sizes of clear-sky ice crystal precipitation observed during the wintertime are between 50 and 200 microns [9]. However, crystals smaller than 50 microns could not be reliably measured on their particle replicator, and smaller particles were not reported. Stone infers cloud properties of Antarctic clouds during the wintertime from radiometric profile measurements, and estimates most clouds are optically thin and composed of small particle sizes on the order of 4 to 16 microns [10]. Lubin and Harper retrieve cloud particle sizes using AVHRR infrared radiances, and estimate that the mean summer and winter effective radii over the South Pole are 12.3 and 5.6 μm, respectively [11]. Mahesh et al. determined cloud particle effective radii from their 1992 data, and obtained a median particle size of 15 μm; in their study, the effective radii of particles larger than 25 microns could not be accurately determined, and only a lower limit to those particles is given. A particular seasonal pattern observed here indicated that cloud particle sizes in winter mostly ranged between 10 and 20 μm, whereas in summer larger particles, with effective radii larger than 25 μm, were dominant.

c. Cloud height and optical depth

Over much of the Antarctic plateau, surface observations of cloud cover are constrained by the absence of topographical reference points. Mahesh et al. use a modified version of the CO_2-slicing method to determine the base height of clouds, from longwave spectral observations. The cloud bases have a bimodal distribution, with the primary maximum in the surface-based inversion layer, and a seasonally dependent secondary maximum between 2.0 and 2.5 kilometers. The higher clouds, i.e. most of the clouds with bases in the 2.0 - 2.5 km range have smaller optical depths (less than 1), whereas clouds with bases near the surface are often thicker, although many of these too have optical depths of less than 2.

Ice crystal precipitation can have a wide range of optical depths, but it is commonly much thicker during the winter. Wilson et al. report wintertime observations of ice crystal optical depths between 2.7 and 10.7, although thicknesses as large as 21 have been measured [13]. In the Arctic springtime, the observed thicknesses ranged from 0.015 to 1.9. Mahesh et al.'s findings of cloud optical depths confirmed the generally held view that clouds over the Antarctic plateau are much thinner than those at the coasts of the continent. Nearly 95% of the clouds at South Pole station were seen to have optical depths smaller than 5. However, no significant seasonal variation in cloud optical depths were seen.

3. Computation of altitude biases

a. Results

The observations summarized in Section 2 indicate some variability in polar cloud properties that would lead to changes in the GLAS altitude bias. To estimate the mean altitude bias for a particular period, the Monte Carlo path delay results from DSE can be weighted by the climatological frequency of various cloud types. In this paper, we apply the Monte Carlo calculations to the ground-based measurements from Mahesh et al., and their findings on cloud heights, particle sizes and optical depths. GLAS will likely see cloud conditions over the Antarctic Plateau that are not identical with those from 1992; nevertheless these data represent the best combination of several cloud properties relevant to multiple-scattering induced delay from the same set of clouds.

Not all clouds, however, will contribute to the altitude bias since many willbe too thick to be penetrated by the GLAS lidar. According to the specifications of the GLAS mission, clouds with a two-way transmissivity of less than 0.25 would not included in any altimetry estimates. For the geometry of the GLAS lidar, the Monte Carlo calculations by DSE show that when forward scattering is considered the optical depth limit corresponding to the above transmissivity is as large as 2. At South Pole, this upper limit to cloud optical depth still permits the use of nearly 75% of the observations from 1992. Moreover, since the scattering-induced delay increases in magnitude with optical depth, one might consider limiting the determination of altitude to those observations where clouds are not very thick, say, with a smaller optical depth, such as 1.0 or even 0.5. The drawback in such an approach is that an increasingly lower threshold of acceptable cloud optical depth eliminates greater numbers of the observations from consideration. Nevertheless, some of the results here are also presented for such smaller subsets of the measurements from the entire year.

Figure 2 shows a histogram of scattering-induced altitude bias expected in GLAS measurements from cloud properties in 1992. Observations of clouds from the South Pole 1992 dataset were used to compute, by Monte Carlo calculations, the altitude bias that would result, from each combination of cloud height, particle radius and optical depth. Consistent with indications from radiosonde data taken during the year, a typical cloud thickness of 1 km was used. Mahesh et al. determined only a lower bound in particle radius in a number of summer-time cases, and in a few mostly winter cases of thick clouds, only a lower limit to the optical depth was determined. The Monte Carlo calculations used to obtain the values in Figure 2 were run only for those observations (approximately three-fourths of the total number of observations) in which both particle radius and optical depth were known. The entire dataset of values, including those omitted in Figure 2, is shown in Figure 3, where the instances of observations using lower limits are specifically indicated as those with only a lower limit to optical depth (diamonds), those with only a lower limit to particle size (open circles) and those with only a lower limit to both particle radii and optical depths (filled circles) known. In these special cases, it must be assumed that the altitude bias corresponding to scattering-induced delay is at least as large as indicated in Figure 3. The median value of the altitude bias for the entire year is 10.8 cm, and the mean is 16.2 cm.

For a given value of the optical depth, the bias in altitude can be expected change due to variations in both particle size and in the height of the cloud above the surface. Low clouds scatter photons which, despite the scattered path, still remain within the field of view of the instrument. Scattering by higher clouds, which are more common in the non-winter months (October-March), tends to remove the scattered path lengths from the field of view, thereby biasing the altitude less. With increasing particle radius, however, a cloud of a given optical depth will bias the altitude increasingly. That winter altitude biases in Table 1 are smaller than non-winter values appears to suggest that the effect of particle sizes in the non-winter months is more significant than the fact that in winter, clouds occur nearer the surface.

b. Methods to reduce bias

The results presented so far assume the altimetry measurements will be used as a “standalone" measurement, with no information available on cloud properties. However, cloud information from the atmospheric channel (532 nm) could provide estimates of cloud optical depth that may beused to reduce the altitude bias [17]. For example, the altitude bias could be reduced by modifying the cloud optical depth threshold for acceptable GLAS observations. Additionally, biases could be reduced by using a more sophisticated method to analyze the lidar surface returns. Both approaches are discussed below.

From the entire set of observations, subsets can be selected using lower optical depth thresholds. Table 1 shows the seasonal and annual values of the altitude biases obtained using several different thresholds - 0.1, 0.5, 1.0 and 2.0 - along with the numbers from all observations. Since very few clouds at South Pole (approximately 10-15%) have optical depths larger than 2, the bias obtained with the cloud optical depth threshold set to 2 is not significantly different from the bias obtained from all the data. However, as the optical depth threshold is lowered, the altitude bias drops correspondingly. The values in altitude bias obtained at the lowest threshold shown (0.1) approach the GLAS requirements to detect secular changes in ice thickness as small as 1.5 cm a year.

An alternate approach to limiting the bias in estimated altitudes is to use a more sophisticated algorithm to analyze the GLAS measurements. The Gaussian fit method described in paper 1 (DSE), for example, eliminates a significant fraction of the scattering-induced delay. Table 2 shows calculations of scattering-induced delays obtained from this method; this table is readily comparable to Table 1. The median altitude bias obtained with this fit is nearly 40% smaller in winter, and one-third smaller during the other months; the mean values are reduced by even greater amounts. At very low optical depths, the altitude bias averaged over the entire year is within the GLAS mission requirement of 1.5 cm.

c. Variability in altitude bias.

If the altitude bias were invariant from one year to another, errors introduced into altimetry measurements as a result of multiple scattering could be neglected, since the objective, namely to determine interannual changes in elevation, could still be fulfilled. However, since the properties of clouds which cause delay by multiple scattering are not constant from one year to the next, the bias varies as well. To estimate the uncertainty in altimetry that will result from such variability, we may consider the average, as well as the extremes of variability in cloud cover over the Antarctic plateau.

The average interannual variation in summer cloud cover at the South Pole from Hahn et al. is about 5 percent, while it is 11 percent during the winter [6]. To assess the impact of this variation on altimetry measurements, we must additionally know the variation in their optical thicknesses, particle sizes, and the heights at which they occur. If in any given year the additional (or fewer) clouds seen are negligibly different in their average properties than those seen in the 1992 dataset, then we may well see no change in the altitude bias using data from a different year. If, on the other hand, there is variation in the cloud properties, which on average is different from those seen in 1992, the average biases computed in Table 1 will increase or decrease correspondingly.

By assuming how this variation is distributed among various optical depths, we can assess the variability in the interannual bias, and its potential impact on altimetry measurements. Whereas this procedure is not intended to produce an estimate of the average variability in the bias, it nevertheless gives us an idea of the bounds of such variability. By removing (or adding) the clouds with the most and least impact on altitude biases from the 1992 data in proportion with the estimated variability in the cloud cover (5% in summer, 11% in winter), we can obtain new annual average bias values.

The altitude biases obtained by considering such deviance from the optical depths seen in 1992 are tabulated in Table 3. As is expected, the addition of thick clouds increases the values of the seasonal and annual altitude biases, as does the removal of thin clouds. Conversely, the addition of thin clouds, or the removal of thick clouds, reduces the average altitude bias. Both the seasonal numbers as well as the annual average change in the altitude bias from 1992, shown in the last column of the table, are greater than the GLAS mission requirement value (1.5 cm) itself.

A second calculation can also be made using the maximum reported variability (13% in summer, 27% in winter) in inter-annual cloud cover instead of the average values, also from Hahn et al.'s measurements. As was done in obtaining values for Table 3, in this case too, the additional (or fewer) clouds are viewed to be entirely of the extreme optical depth regimes, and the annual average biases in the altitude are computed again; these numbers are shown in Table 4. Expectedly, the seasonal and annual bias values are now even more different from the 1992 numbers, up to three or four times the GLAS mission specification.

These numbers suggest that the average variation in cloud cover and optical thickness from one year to another, using a multi-year average estimate of such variability from Hahn et al., is produces variation in the altitude bias that is significant. The values of such variability, being comparable to or greater than the GLAS mission specification, will clearly impede the reliable determination of altitude changes from one year to the next. Indeed, the most advantageous of the various changes considered in Tables 3 and 4 still produces bias variations of 1 to 1.5 cm.

Similar assessments can also be made with changes in particle sizes instead of or in addition to optical depth changes. The results for which we have shown results in Table 3 and 4 implicitly assume that any additional or less cloud cover in other years will have particle sizes distributed seasonally the same way as in 1992; the potential impact of particle size changes, though, cannot be overlooked. However, our intention here is to suggest that variability in cloud cover can manifest itself in variations in the altitude bias of GLAS measurements from one year to another. Without quantifying the potential impact on altitude bias from every conceivable change in cloud characteristics, we have attempted to define some range of values to such variability. This effort appears to show that variation in the altitude bias could be of the same magnitude as the accuracy requirement specified for the GLAS mission itself. Thus, a determination of altitudes, already uncertain due to the presence of clouds, must additionally be reconciled with year-to-year changes in the uncertainty in such measurements.

d. Bias in clear-sky observations

As stated earlier, the altitude bias can be held to small values if we selectively exclude observations that include clouds of relatively large optical depths. It would be especially advantageous, in fact, to limit the determination of altitude to those observations which are made under known clear-sky conditions. The use of the atmospheric channel on GLAS could permit such a determination, so that the 1064 nm channel is not used as a standalone observation. There is, however, an additional concern, namely blowing snow.

Throughout much of the Antarctic plateau, downslope surface winds known as katabatic winds are prevalent during much of the year. The settling of cold air at the higher elevations of the plateau creates these surface winds, which can disturb loose and recent snow. Visual observations made by the surface weather observers at South Pole station indicate blowing snow conditions in up to a third of all observations. (NEED A REFERENCE HERE). Blowing snow is typically not very optically thick, and spectral measurements used in Mahesh et al. suggest that an optical depth of 0.1 is as thick as the snow may be.

The concern for GLAS, however, is not the optical depth of the snow, but its proximity to the surface. When a scattering layer is close to the surface (blowing snow typically extends from the surface up to the lowest 100-300 meters) photons scattered by it nevertheless remain within the footprint of the GLAS measurement. As a result, the delay in their travel times caused by such scattering becomes included in altimetry calculations. This means that even if GLAS altimetry is limited to nearly or entirely cloud-free conditions, the altitude values obtained from them might be in error.

Using typical values of height, particle size and optical depth for blowing snow, the Monte Carlo calculations were performed as before to obtain an estimate of the altitude bias due to blowing snow. Figure 4 shows the altitude bias due to blowing snow for two different optical depths (filled circles and squares) at several different physical thickness values for the snow layer. Also shown are the lower bias estimates obtained when the calculations are repeated with the Gaussian fit (corresponding open circles and squares) described in DSE. A blowing snow layer 300 m thick with an optical depth between 0.05 and 1.0 will bias the altitudes derived by between 1.4 and 3.0 cm approximately; this bias can be considerably reduced (to between 0.2 and 0.7 cm) by the use of the Gaussian fit method to determine the centroid of the return pulse. Even these reduced values, it must be borne in mind, average to about a third of the specified accuracy needed for the GLAS mission.

4. Summary and Conclusions

Atmospheric multiple scattering is potentially a large error source for precision laser measurements of surface altitude as envisioned for the Geoscience Laser Altimeter System (GLAS) or other similar space missions. Also, a survey of polar cloud observations indicates that most of the cloud properties that will affect spaceborne lidar measurements have significant seasonal and interannual variations. A recently completed study of Antarctic cloud properties has made it possible to quantify the potential impacts of such clouds on GLAS altitude measurments, and to assess the likely inter-annual variability in altitude bias that results from year-to-year variation in the relevant cloud properties.

From cloud property information collected at the South Pole and the path delay data from DSE, estimates of the mean Antarctic summer and winter altitude bias were computed. The bias in altitude introduced by clouds in the path of the lidar pulse appears to be significant, and is almost always larger than the accuracies specified for the mission. Altimetry measurements could be confined to those observations made from the satellite which are known to be under cloud-free or thin-cloud conditions; this reduces the altitude bias a great deal, but even these smaller biases are not negligilbe. Under thin clouds, for example, the bias, as well as the inter-annual variability in the bias, may preclude the accuracies needed to measure inter-annual changes in ice sheet thickness. However, more sophisticated waveform analysis techniques than simply accepting the centroid of the return pulse for delay calculations, such as the one suggested in DSE, reduce these biases even further.

To overcome the limitations in altimetry measurements caused by the bias resulting from scattering within cloud layers, ice sheet elevations may need to be determined only from cloud-free observations. This requires that the atmospheric channel at 532 nm be used in cloud-detection, alongside the 1064 nm channel's altimetry capability. Even with this additional precaution, near-surface blowing snow conditions which occur frequently will remain unaccounted for; the proximity of the snow to the surface makes this scattering layer more potent (per unit optical depth) than clouds, since scattered, delayed photons remain within the field of view of the instrument. An altitude bias of 1-3 cm from the snow layer alone is likely. However, as with clouds, the use of improved methods to analyze the return pulse does help in substantially reducing the bias.

The upcoming GLAS mission, by monitoring of ice-sheet altitude changes over Antarctica and elsewhere, is expected to provide information on whether global warming is affected an important region of the planet. Potential melting of ice sheets from global warming will likely lead to significant rises in sea level, and consequently to catastrophic outcomes along coastlines around the world and in many island nations. This paper suggests that the measurement accuracies necessary to permit the required monitoring are achievable only under conditions of thin or no cloud cover. Careful selection of data from which GLAS altimetry measurements are made is therefore necessary.

A factor that has not been included in this analysis is the effect of surface slope on the altitude bias. The results of DSE suggest that sloped surfaces may obscure the effects of cloud multiple scattering on the path delay, and make the determination of the return pulse centroid more di?cult. In addition, other factors such as signal noise and surface roughness have not been examined. It is possible that these factors would also reduce the effectiveness of Gaussian fitting on the path delay, and other forms of return pulse analysis may be required to reduce altimetry biases to acceptable levels. Further study will be necessary to determine how signal noise, rough, sloped surfaces and advanced waveform analysis of the return pulse may affect the multiple scattering-induced altitude bias.

Acknowledgements.

Part of this work was supported by USRA contract NAS5-32484, and by NASA contracts NAG5-33015 and NAG5-7522. The total cloud cover database of Hahn et al. was provided by the U.S. Department of Energy through its Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory.

REFERENCES

[1] W. Krabill, R. Thomas, K. Jezek, K. Kuivinen, and S. Manizade, "Greenland ice sheet thickness changes measured by laser altimetry," Geophys. Res. Lett., vol. 22, pp. 2341-2344, 1995.

[2] H. J. Zwally, A.C. Brenner, J. A. Major, R. A. Bindschadler, and J. G. Marsh. "Growth of the Greenland ice sheet: Measurement," Science, vol. 246, pp. 1587-1589, 1989.

[3] S. Cohen, J. Degnan, J. Bufton, J. Garvin, and J. Abshire, "The geoscience laser altimetry/ranging system," IEEE Trans. Geoscience Remote Sensing, vol. GE-25, pp. 581-592, 1987.

[4] GLAS Science Team, "Geoscience Laser Altimeter System Science Requirements," NASA Earth Observing System Reference Document, 1997.

[5] D. P. Duda, J. D. Spinhirne, and E. W. Eloranta, "Atmospheric multiple scattering effects on GLAS altimetry. Part I: Calculations of single pulse bias," Submitted to IEEE Trans. Geoscience Remote Sensing, 13 pp., 1999.

[6] C. Hahn, S. Warren, and J. London, "Climatological data for clouds over the globe from surface observations, 1982-1991: Data tape documentation for the total cloud edition," Numerical data package NDP-026A, Available from Carbon Dioxide Information Analysis Center, Oak Ridge National Lab, 1995.

[7] Japan Meteorological Agency, "Climatological data at Syowa station, Antarctica," Antarct. Rec., vol. 73, pp. 273-303, 1981.

[8] J. A. Curry, W. B. Rossow, D. Randall, and J. L. Schramm, "Overview of Arctic cloud and radiation characteristics," J. Clim., vol. 9, pp. 1731-1764, 1996.

[9] V. N. Smiley, B.M.Whitcomb, B. M. Morley, and J. A. Warburton, "Lidar determinations of atmospheric ice crystal layers at South Pole during clear-sky precipitation," J. Appl. Meteor., vol. 19, pp. 1074-1090, 1980.

[10] R. S. Stone, "Properties of austral winter clouds derived from radiometric profiles at the South Pole," J. Geophys. Res., vol. 98, pp. 12,961-12,971, 1993.

[11] D. Lubin, and D. A. Harper, "Cloud radiative properties over the South Pole from AVHRR infrared data." J. Climate, vol. 9, pp. 3405-3418, 1996.

[12] A. Mahesh, V. P. Walden, and S. Warren, "Ground-based remote sensing of cloud properties over the Antarctic Plateau. Part I: Cloud Base Heights, and Part II: Cloud Optical Depths and Particle Sizes", Journal of Applied Meteorology, in press, 2000.

[13] L. D. Wilson, J. A. Curry, and T. P. Ackerman, "Satellite retrieval of lower-tropospheric ice

crystal clouds in the polar regions," J. Climate, vol. 6, pp. 1467-1472, 1993.

[14] V. P. Walden, and S. G. Warren, \A spectral downward longwave climatology for clear and cloudy skies over South Pole," IRS '96: Current Problems in Atmospheric Radiation, W. L. Smith and K. Stammes, Eds., A. Deepak, Hampton, VA, pp:54-57, 1996.

[15] J. A. Curry, and E. E. Ebert, \Annual cycle of radiation uxes over the Arctic Ocean: Sensitivity to cloud optical properties," J. Climate, vol. 5, pp. 1267-1280, 1992.

[16] J. A. Curry, J.L. Schramm, and E. E. Ebert, \Impact of clouds on the surface radiation balance of the Arctic Ocean," Meterol. Atmos. Phys., vol. 51, pp. 197-217, 1993.

[17] J. D. Spinhirne, and S. P. Palm, "Space based atmospheric measurements by GLAS," Advances in Atmospheric Remote Sensing, Ansmann (Ed.), Springer, Berlin, pp. 213-216, 1997.

List of Figures

Figure 1. Mean annual cloud cover over the Arctic derived from [6].

Figure 2. Histogram of scattering-induced altimetry errors obtained by Monte Carlo calculations, using cloud properties during 1992. The median value is 11.9 cm. The bias is calculated only for those cases where both the optical depth of the cloud, and effective particle radii for ice crystals in it, were both known. These account for about 73% of all the clouds observed during 1992.

Figure 3. Multiple-scattering induced altitude bias from all observations of clouds during 1992, obtained by Monte Carlo calculations. The pluses (+) represent data when both cloud optical depth and particle radius are known. In other cases, only a lower limit to the scattering induced delay is calculable, either because only a lower limit to the optical depth is known (diamonds), or only a lower limit to the particle effective radius is known (open circles), or both (filled circles).

Figure 4. Scattering-induced altitude bias from blowing snow. Results are shown for two different optical depths, using both the centroid of the return pulse, as well as the Gaussian fit discussed in DSE. The filled circles are at an optical depth of 0.1 and the filled squares at an optical depth of 0.05; each of these were obtained from the centroid of the return pulse. The corresponding values obtained from the Gaussian fit at the two optical depths, are shown as open circles and squares respectively.

Table 1: Seasonal and annual average values of multiple-scattering induced bias in surface elevation at South Pole, for several subsets of the measurements from 1992. The subsets are chosen using varying optical depth thresholds; as thicker clouds are excluded from consideration, the scattering-induced delay becomes smaller.

	WINTER (April-September)		**NON-WINTER** (October-March)		**All year** (1992)	
	Median	**Mean**	**Median**	**Mean**	**Median**	**Mean**
all clouds	8.66	14.57	14.46	21.31	10.82	16.18
$\tau < 2$	7.05	9.73	13.91	15.97	8.76	11.25
$\tau < 1$	5.29	6.46	10.49	10.79	5.97	7.25
$\tau < 0.5$	4.12	4.67	5.48	6.29	4.15	4.87
$\tau < 0.1$*	1.89	2.00	1.94	1.97	1.89	2.00

*Between October and March, i.e. during the non-winter months, no clouds were observed with optical depths smaller than 0.1, the values listed in the table are from the thinnest cloud observed during that period, on October 5, 1992, with optical depth 0.16.

Table 2: Identical to Table 1, except that the multiple-scattering induced biases were obtained in this case using the Gaussian fit method described in DSE.

	WINTER (April-September)		**NON-WINTER** (October-March)		**All-Year** (1992)	
	Median	**Mean**	**Median**	**Mean**	**Median**	**Mean**
all clouds	5.03	6.55	9.51	10.45	5.64	7.50
$\tau < 2.0$	3.85	4.76	9.17	8.42	5.03	5.65
$\tau < 1.0$	3.09	3.62	5.45	5.67	3.29	3.99
$\tau < 0.5$	2.49	2.75	3.14	3.48	2.53	2.85
$\tau < 0.1$*	1.19	1.22	1.71	1.71	1.19	1.22

* Between October and March, i.e. during the non-winter months, no clouds were observed with optical depths smaller than 0.1, the values listed in the table are from the thinnest cloud observed during that period, on October 5, 1992, with optical depth 0.16.

Table 3: Altitude bias values, and changes in those values from 1992 annual and seasonal averages, assuming that average year-to-year variation in cloud cover (5% in the summer, 11% in the winter) is contained entirely in either thick (τ>2) clouds or in thin (τ<2) clouds.

	More clouds than in 1992		**Fewer clouds than in 1992**		**Average variability from 1992**
	thick	**thin**	**thick**	**thin**	
summer	23.04	20.39	19.40	22.33	1.37
winter	17.40	13.33	11.05	16.13	2.29
all-year	18.41	15.13	13.56	17.42	1.78

Table 4: Altitude bias values, and changes in those values from 1992 annual and seasonal averages, assuming that extreme year-to-year variation in cloud cover (13% in the summer, 27% in the winter) is contained entirely in either thick (τ>2) clouds or in thin (τ<2) clouds.

	More clouds than in 1992		**Fewer clouds than in 1992**		**Average variability from 1992**
	thick	**thin**	**thick**	**thin**	
summer	25.48	19.08	15.89	24.20	3.68
winter	20.65	11.90	4.01	19.23	5.99
all-year	21.20	13.82	8.66	19.73	4.61